Jet Propulsion Laboratory
California Institute of Technology

INTEGRATED MODELING AND SIMULATION OF AUTONOMOUS PARAFOIL DESCENT ON TITAN

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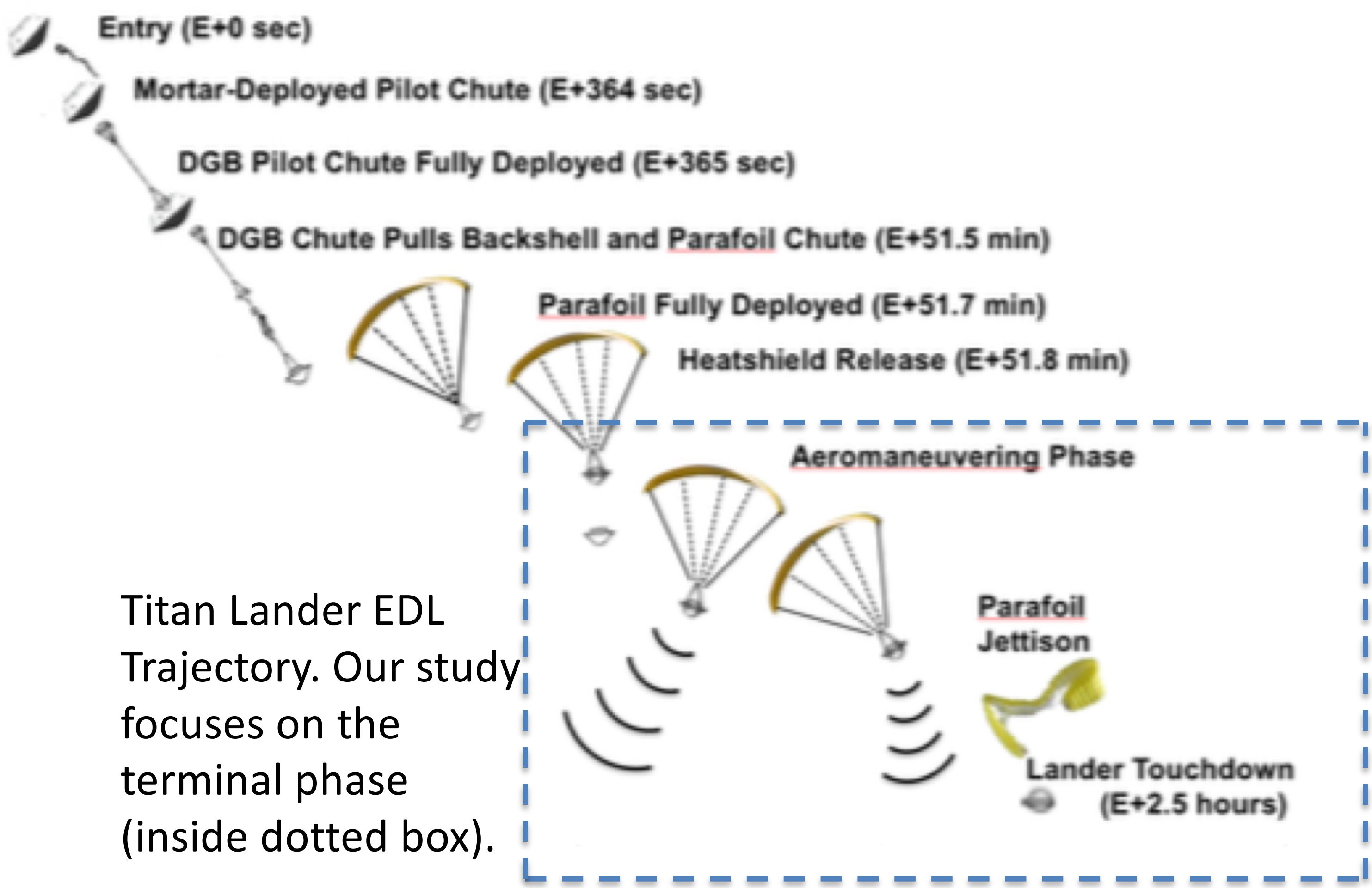
Guided Descent to Landing on Titan

Why landing on Titan?

- Gases and liquids similar to Earth's
- Possible presence of underground oceans of water

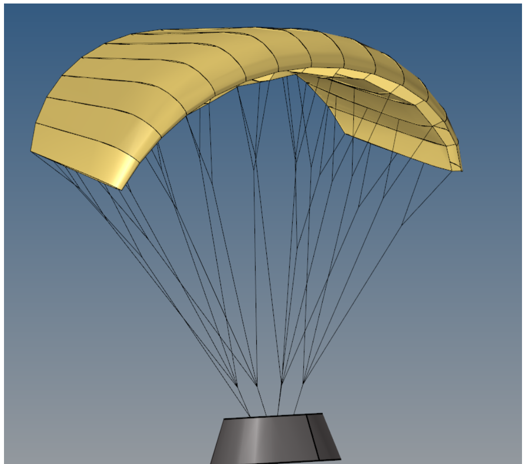
Why use a parafoil?

- Cost-effective
- Ease of deployment
- Low mass compared to payload
- Precise autonomous delivery

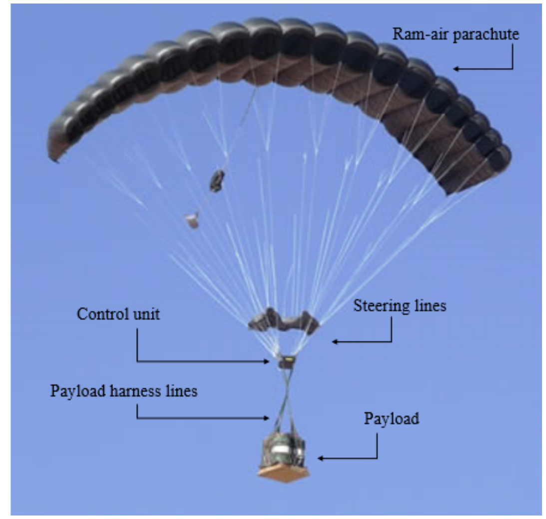


Titan Lander EDL Trajectory. Our study focuses on the terminal phase (inside dotted box).

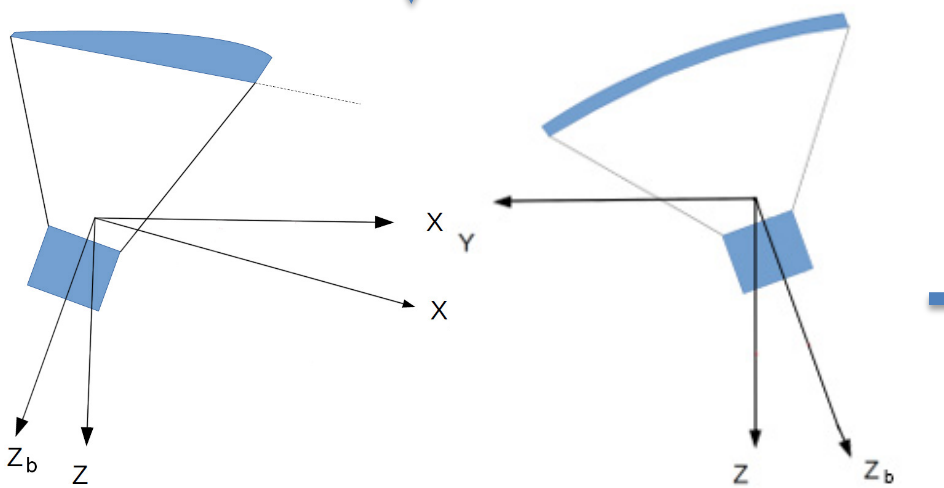
Model development and comparison to terrestrial parafoils



COLDTech Prototype

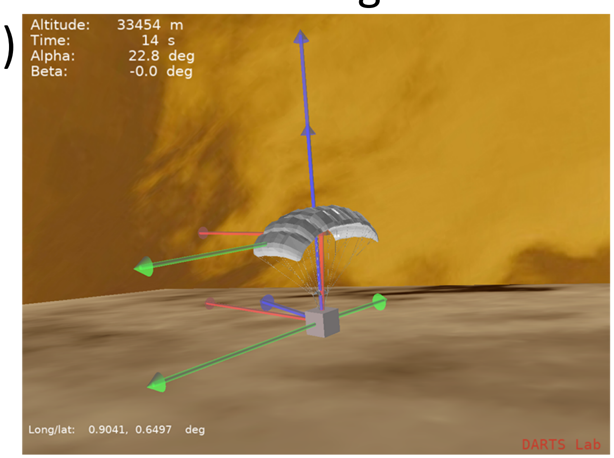


Parafoil main components.



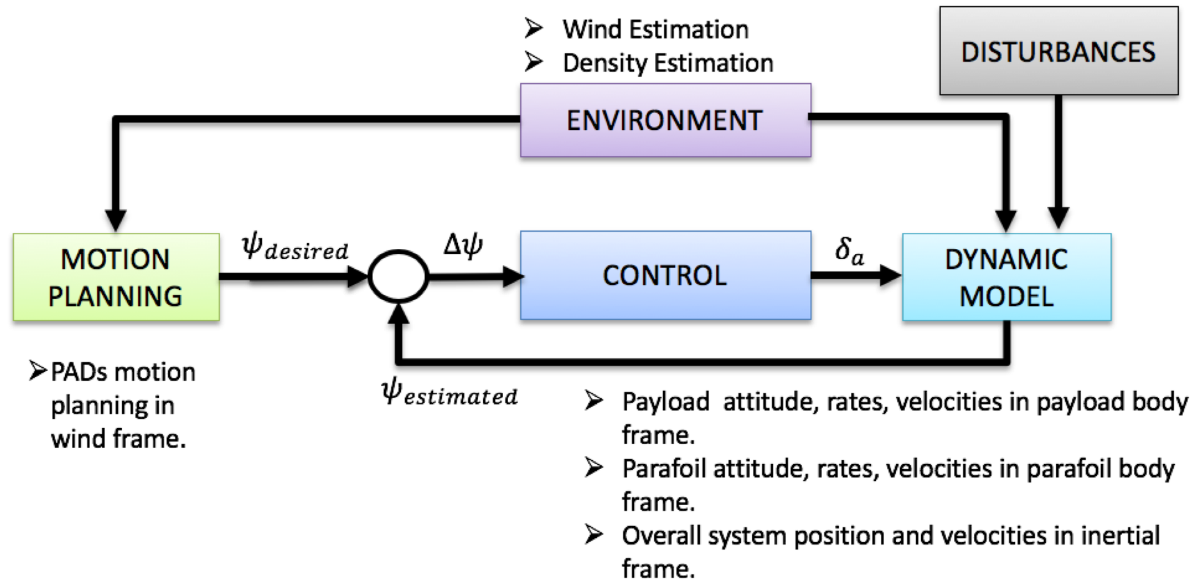
Parafoil+payload mathematical models for G&C analyses of terminal descent

Parafoil terminal descent physics-based models and simulation in our in-house Dynamics Simulator for Entry, Descent and Landing (DSENDS)



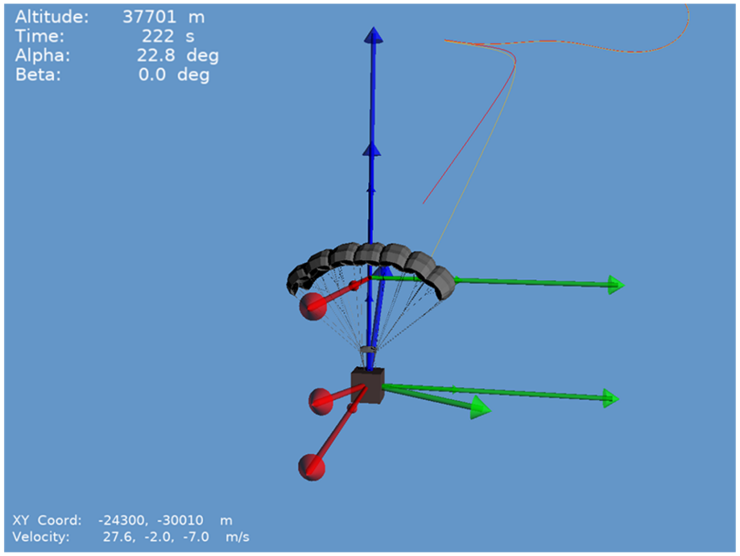
Guidance and Control (G&C)

- The Guidance & Control aspects are divided into three parts:
  - a heuristic approach (T-approach) for which no previous motion planning is required,
  - optimal trajectory planning,
  - optimal trajectory tracking.



- Implemented planning and control algorithms for all phases of parafoil guided descent:
  - Homing: parafoil deployment to vicinity of target: Turn and straight line flight
  - Energy management: vicinity of target to low altitude: "T-approach" with figure-8 turns to reduce altitude
  - Final approach: Multiple algorithms tested with increasing accuracy and computational complexity
  - Flare: Work in progress, to reduce touchdown velocity

Dynamics



δ_l: left flap deflection

δ_r: right flap deflection

$$\delta_s = \frac{1}{2}(\delta_r + \delta_l)$$

$$\delta_a = \delta_r - \delta_l$$

- **Aerodynamic forces and moments**
- Buoyancy force
- Canopy and payload weight forces

$$\boldsymbol{x} = \left[u, v, w, p, q, r, x, y, z, \phi, \theta, \psi\right]^T$$

6-DoF model assumptions:

- Canopy and payload rigidly connected
- Six aerodynamic forces/moments on canopy
- Drag acting on payload
- Drag acting on suspension lines
- Buoyancy force
- Weight forces

Linearization $\Delta\dot{\boldsymbol{x}} = \boldsymbol{A}\Delta\boldsymbol{x} + \boldsymbol{B}\Delta\boldsymbol{u}$

Longitudinal and lateral dynamics can be studied independently:

$$\boldsymbol{x}_{lon} = [u, w, q, \theta]^T \quad \text{with} \quad u = \delta_s$$

$$\boldsymbol{x}_{lat} = [v, p, r, \phi, \psi]^T \quad \text{with} \quad u = \delta_a$$

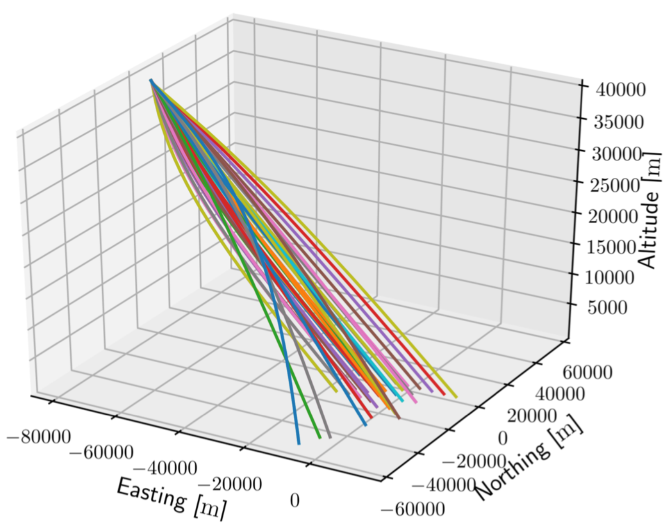
Stable and controllable

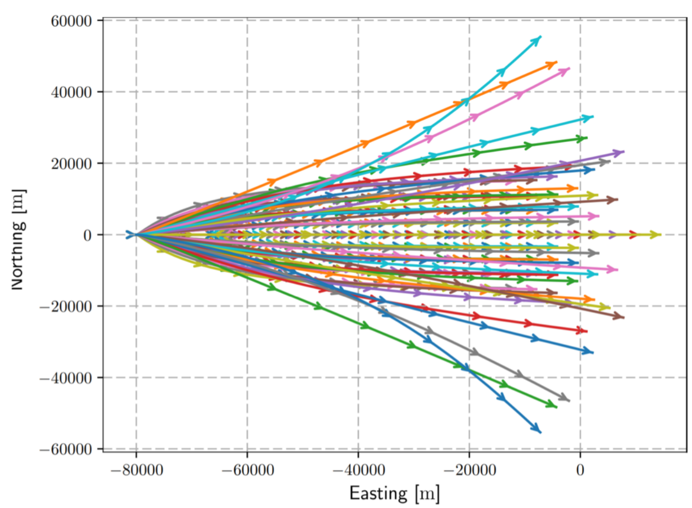
Reachability Analysis – Divert Range and Wind Effect

- A complete 40 km descent was simulated for glide ratios 2 and 3 in different conditions: no wind, upwind, and downwind descent (values in meters)

Glide ratio (L/D)	Upwind divert range	No wind divert range	Downwind divert range
2	74406	77146	78102
3	113647	119734	122015

- Both longitudinal and lateral wind speed were then varied to obtain a map of expected divert ranges



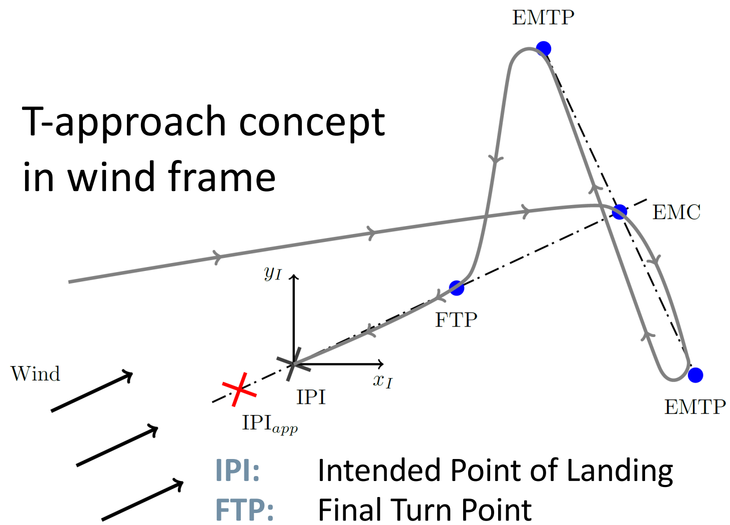


Wind drift under different wind conditions

- Lateral wind drift up to ~ 56 km
- Longitudinal wind drift up to ~ 18 km

T-Approach

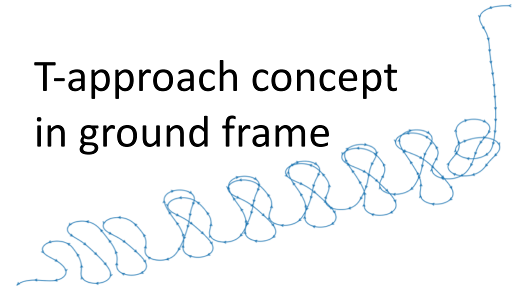
T-approach concept in wind frame



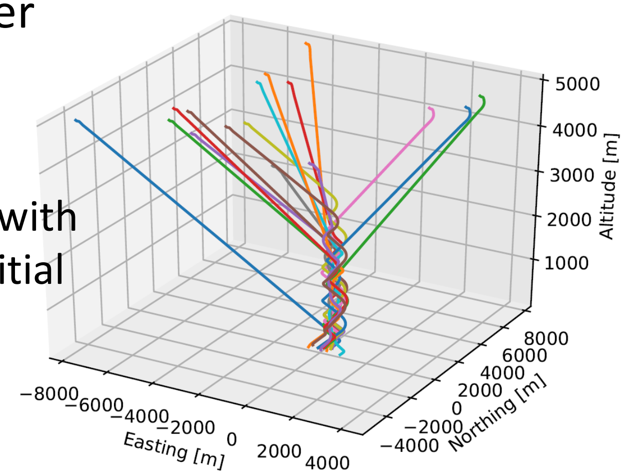
IPI: Intended Point of Landing
FTP: Final Turn Point
EMC: Energy Management Center
EMTPs: Energy Management Turning Points

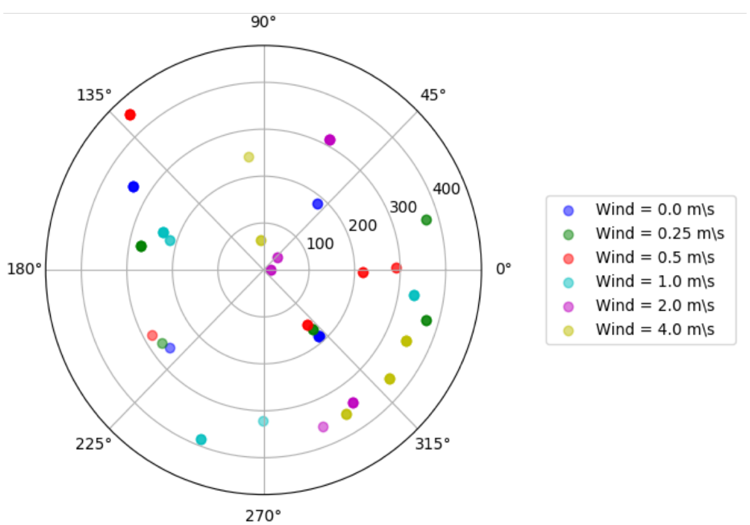
1. Homing: navigate towards EMC
2. Energy management: fly eight-patterns between EMTPs
3. Landing
   a) Approach FTP
   b) Turn into wind
   c) Execute flare maneuver

T-approach concept in ground frame



T-approach simulation with different initial conditions.





Landing dispersion [m] with wind blowing in the East-West direction (0 deg). Wind magnitude given at 5 km altitude.

Monte Carlo simulations from 5 km AGL, perfect state knowledge, typical wind

Final landing error [m] given the starting x,y position and wind speed.

			Wind [m/s]					
			0.00	0.25	0.50	1.00	2.00	4.00
Initial x, y Position [m]	4755	1545	336	274	443	234	314	347
	0	5000	187	167	150	332	343	361
	-4755	1545	184	372	218	386	15	356
	-2939	-4045	184	373	290	217	40	63
	2939	-4045	263	270	282	320	359	243

The results of Monte Carlo simulation (with different starting position/wind speed) indicate a maximum obtained error is 239 m and 332 m along Easting and Northing direction, respectively

Waypoint Trajectory Tracking

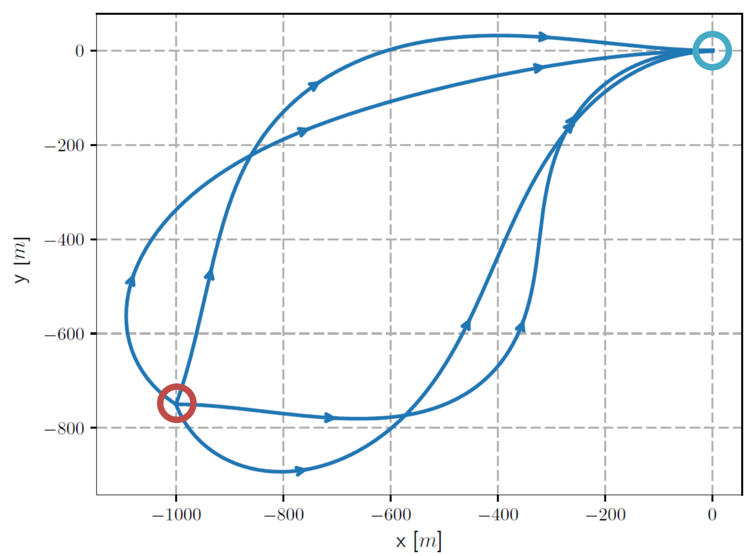
An initial homing phase was considered, during which a minimum-time path (using Linear Quadratic Optimal Control) is followed to reach an area above the target as quickly as possible as to maximize the residual altitude.

Given a sequence of spatial waypoints, a Waypoint-Tracking Model Predictive Control (WT-MPC) allows to accurately track them by linearizing the system at every time step and computing the optimal control action, given a desired time horizon which depends on the available computational power.

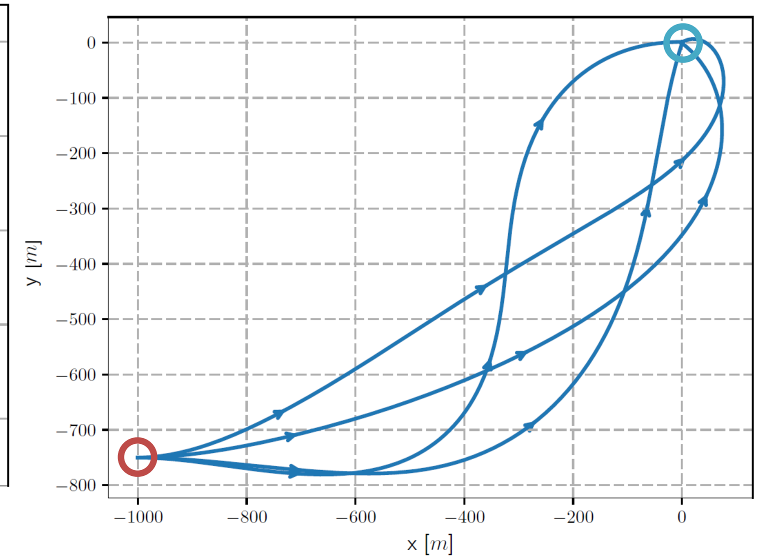
Assumptions:

- Soft constraints on final state
- Weights the distance from target
- Limits control action to limit banking angle

Different initial heading angles, same wind direction



Same initial heading angle, different wind directions



Start End

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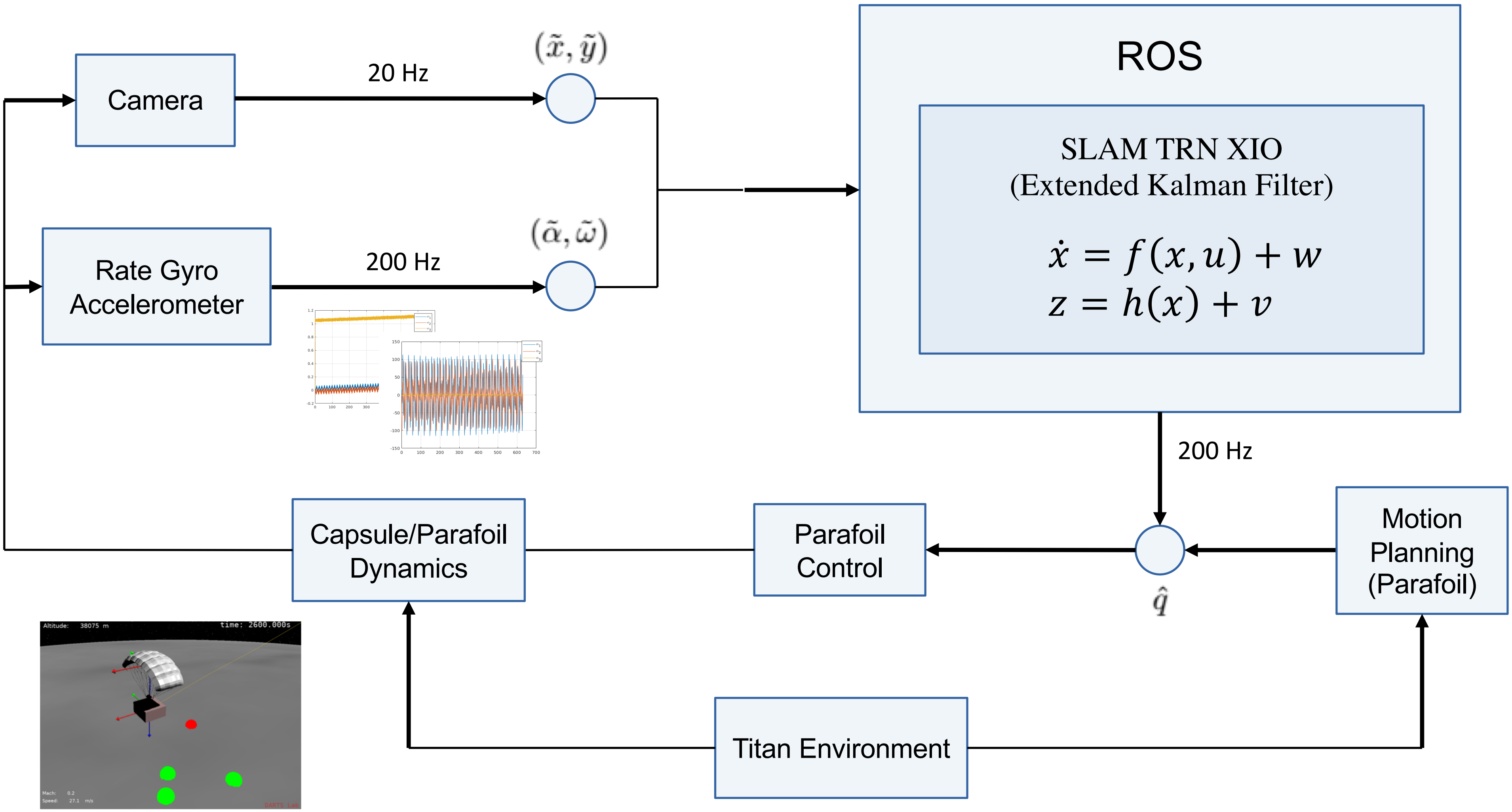
DSENDS E-10 to Ground Simulation

We have extended our in-house Dynamics Simulator for Entry, Descent and Landing (DSENDS) with libraries of vehicle dynamics models to handle the parafoil G&C algorithms proposed here and the specific state estimation, tracking, and control capability in conditions relevant to Titan's environment. TRN estimation is based on a SLAM-MSCKF algorithm and is a key component in this study for determining lander delivery error. For simulation purposes, the TRN estimation is carried out independently from the DSENDS simulation on a Robot Operating System (ROS) node.



Conclusions

We have considered:

- Atmospheric models and system dynamics
- Flare maneuver to reduce the touchdown speed
- A PD controller, T-approach, and optimal trajectories to minimize the final landing error
- JPL DSENDS end-to-end simulation including noisy measurements, state estimation, and vision-based navigation

→ Titan precision landing is feasible, provided sufficient knowledge of the system parameters and atmospheric models

Future Work:

- 9-DOF model implementation, provided sufficiently reliable parameters are available
- Simulation of parafoil behavior during canopy inflation
- Wind/Density estimation and/or analytical model improvement based on available data (e.g. latitude/longitude dependence)